AN EXPERIMENTAL INVESTIGATION TO IMPROVE LEAD ACID BATTERY RECHARGING ALGORITHMS FOR ENVIRONMENTAL PERFORMANCE

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Perform functional testing of lead acid batteries to demonstrate potential improvements to battery charging algorithms Rationale -Improving charging algorithms can improve battery lifetime -Current charging algorithms are constant voltage and may only provide for temperature compensation (if at all) -Variable voltage algorithms that also incorporating state-of-charge compensation can improve battery charge operations -Improving battery state of knowledge (charge status) can extend battery usage beyond SLI (starting, lights, ignition) operations to enable silent watch operations Approach -Characterize lead acid battery performance as a function of temperature -Three test phases identified and are being executed -Characterize battery environmental performance (OCV, resistance and capacity tests according to MIL-PRF-32143A) -Controlled alternator charging performance -Vehicle simulation tests

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Program Overview

POWER AND MOBILITY

Goals

- Perform functional testing of lead acid batteries to demonstrate potential improvements to battery charging algorithms

Rationale

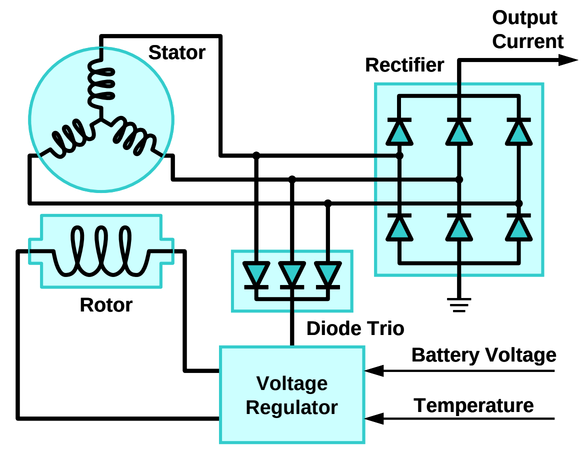
- Improving charging algorithms can improve battery lifetime
    - Current charging algorithms are constant voltage and may only provide for temperature compensation (if at all)
    - Variable voltage algorithms that also incorporating state-of-charge compensation can improve battery charge operations
- Improving battery state of knowledge (charge status) can extend battery usage beyond SLI (starting, lights, ignition) operations to enable silent watch operations

Approach

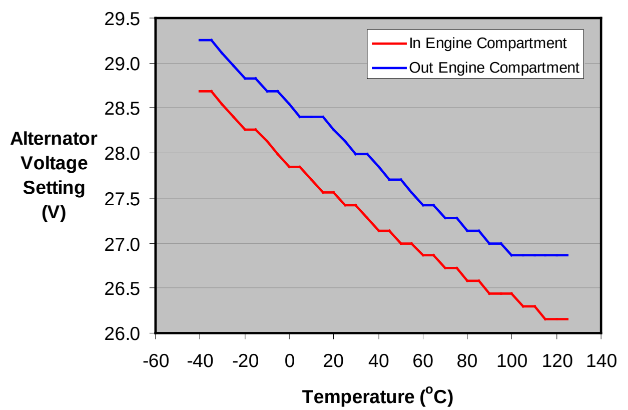
- Characterize lead acid battery performance as a function of temperature
- Three test phases identified and are being executed
    - Characterize battery environmental performance (OCV, resistance and capacity tests according to MIL-PRF-32143A)
    - Controlled alternator charging performance
    - Vehicle simulation tests

Alternator Operations

- Alternators provide current to provide battery charging and vehicle current demands
- Voltage regulator accepts voltage feedback from battery circuit
- Typical alternator circuits employ an adjustable rotor field current to provide desired output voltage (current)
- Alternator *may* employ temperature feedback from battery
    - Different algorithms are employed if batteries are co-located with the alternator (i.e. in engine compartment)
    - Vehicle packaging may dictate other locations
- In general, battery resistance decreases at higher temperatures
    - Reducing alternator output voltage at higher temperature reduces current output for battery recharging
- The greater depth of discharge exercised for silent watch (engine off) operations increases the need for state-of-charge and temperature compensation.



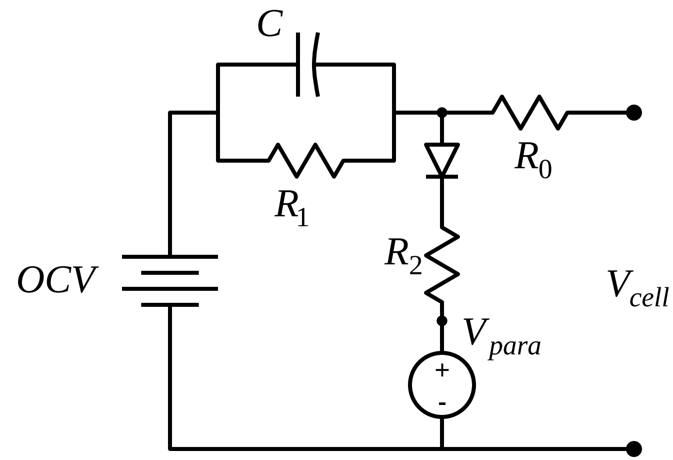
Typical Alternator Layout



Temperature Compensation Exemplar

Battery Equivalent Circuit

- Although many forms of equivalent circuit models exist, the most common form is the Thevinin equivalent circuit
- Battery is characterized by an open circuit voltage (OCV) source in series with an R-C pair and a line resistance, R_0
- A parallel charging resistance leg accounts for parasitic losses during charging operations



Thevinin Battery Equivalent Circuit

- Under steady-state operations (constant current), the battery direct current resistance (DCR) is characterized by the sum of resistances R_1 and R_0
- OCV is a function of battery state-of-charge (SOC)
- Resistance values are a function of battery SOC, temperature and current direction (charging vs discharging)
- Cell voltage (V_{cell}) and hence feedback voltage to the voltage regulator is a function of battery OCV, battery DCR and current demand

Open Circuit Voltage

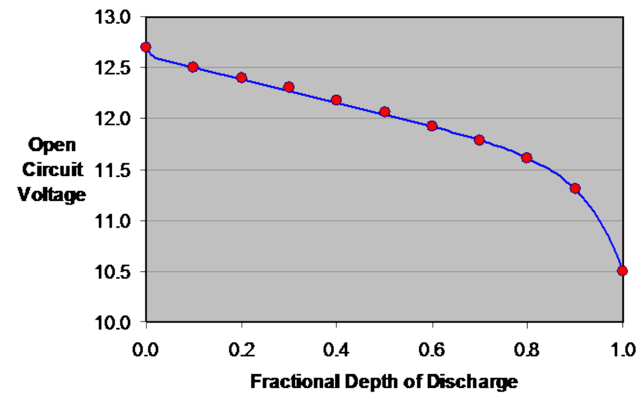
- Open circuit voltage (OCV) is a function of battery state-of-charge (SOC) $OCV = f(SOC)$
- Our suggested OCV correlation form superposes two exponential functions and a linear function

$$OCV = Ae^{-\alpha x} + B[1 - e^{-\beta(1-x)}] + Cx + D$$

$$x = \text{fractional Depth of Discharge } (DOD)$$

$$\text{State of Charge}, SOC = 1 - x$$

- This functional form captures near-full and near-empty nonlinearity, provides great flexibility and avoids inflection points associated with polynomial forms
- Two coefficients are found through boundary conditions (full & empty OCV) and negative slope imposes limits on a third
- Correlations exhibit very satisfactory agreement with manufacturer data



Typical OCV as a function of Depth of Discharge for a VRLA AGM Battery

Coefficient	Value
A	0.086
B	0.969
α	115.664
β	12.203
C	-1.145
D	11.645

OCV Coefficients for VRLA AGM Battery Manufacturer Data

SOC & Battery Capacity (Current Compensation)

- SOC can be determined through Coulomb counting:

$$SOC = SOC_{t=0} - \frac{1}{C}\int_0^t I(\tau)d\tau$$

where C is battery capacity and I is battery current

- However, battery capacity is a function of effective current rate and cell temperature

$$SOC = SOC_{t=0} - \frac{1}{C(\bar{I},\theta)}\int_0^t I(\tau)d\tau$$

- Historically, cell capacity current compensation can be estimated with Peukert's Law

$$C(I) = (I_0/I)^{k-1}C_0$$

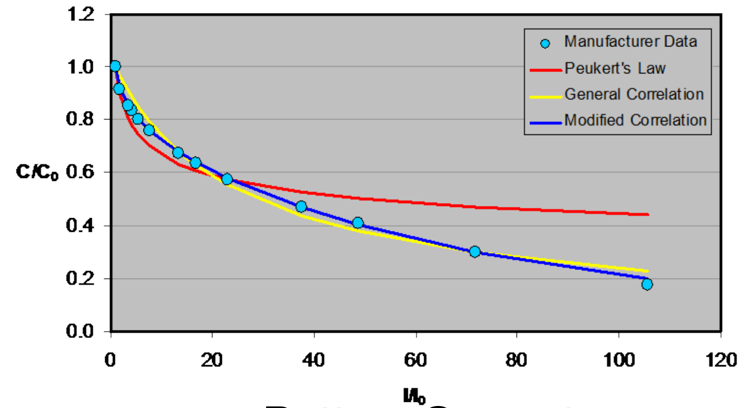
- However, Peukert's Law does not account for temperature effects AND can significantly overestimate capacity at high currents

- A literature survey showed the following general correlation can better estimate performance:

$$C(I) = \frac{\alpha}{1+(\alpha-1)(I/I_0)^{\beta}}C_0$$

- However, a modified correlation shows better agreement with manufacturer data

$$C(I) = \frac{\alpha(I/I_0)^{\gamma}}{1+(\alpha-1)(I/I_0)^{\beta}}C_0$$



Battery Current Compensation Correlations

	General Correlation	Modified Correlation
α	1.073	1.001
β	0.808	1.532
γ	N/A	-0.122

Current Compensation Correlation Coefficients

Battery Capacity (Temperature Compensation)

- Temperature compensation looks to correct battery capacity
- A simple product solution is desired to couple the current and temperature compensation into a single form

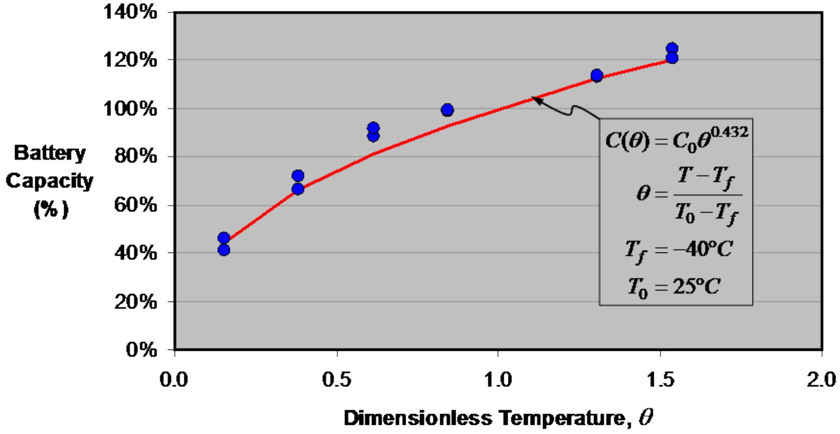
$$C(I,\theta) = f_I(I)\, f_\theta(\theta) C_0$$

- For temperature compensation, we propose a power law of the form:

$$C(\theta) = C_0 \theta^\delta$$

where θ represents the dimensionless battery temperature

$$\theta = \frac{T - T_f}{T_0 - T_f}$$



Measured VRLA AGM Battery Capacity Compensation and Temperature Correlation

- Limits in the dimensionless temperature have been chosen around the rated (nameplate) temperature, T_0, and the approximate electrolyte freezing temperature, T_f

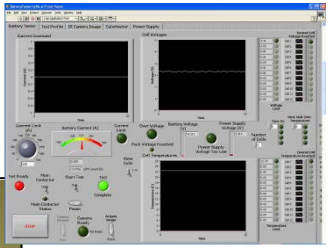
$$T_0 = 25°C \quad and \quad T_f = -40°C$$

- General form of the battery capacity compensation correlation:

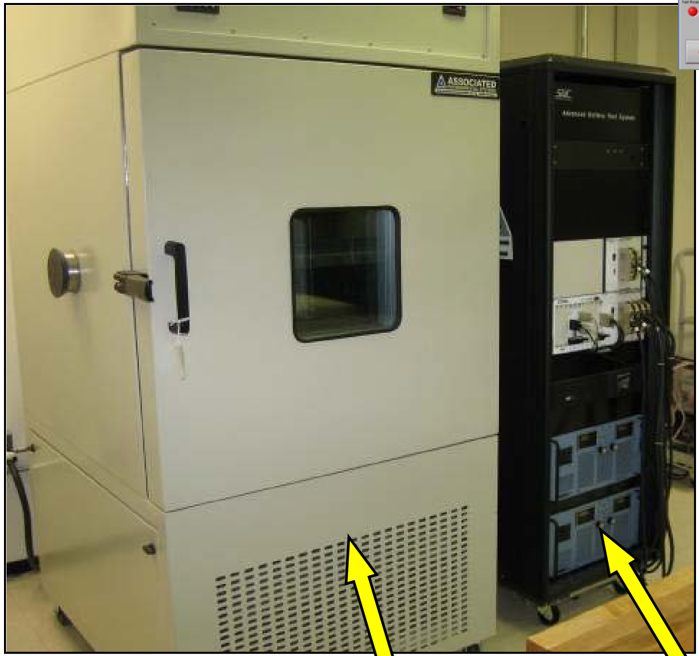
$$C(I,\theta) = \frac{\alpha (I/I_0)^\gamma \theta^\delta}{1 + (\alpha - 1)(I/I_0)^\beta} C_0$$

Environmental Testing
(Key Apparatus)

- Primary environmental testing utilizes the SAIC-developed Advanced Battery Tester coupled to an environmental chamber
- Environmental chamber allows for controlled ambient conditions / battery tempering
- Battery tester allows for programmable time-variant test load profiles under a variety of conditions
- Custom software allows for real-time data display, processing and storage
- Instrumentation includes current, voltage and temperatures



Battery Tester Software

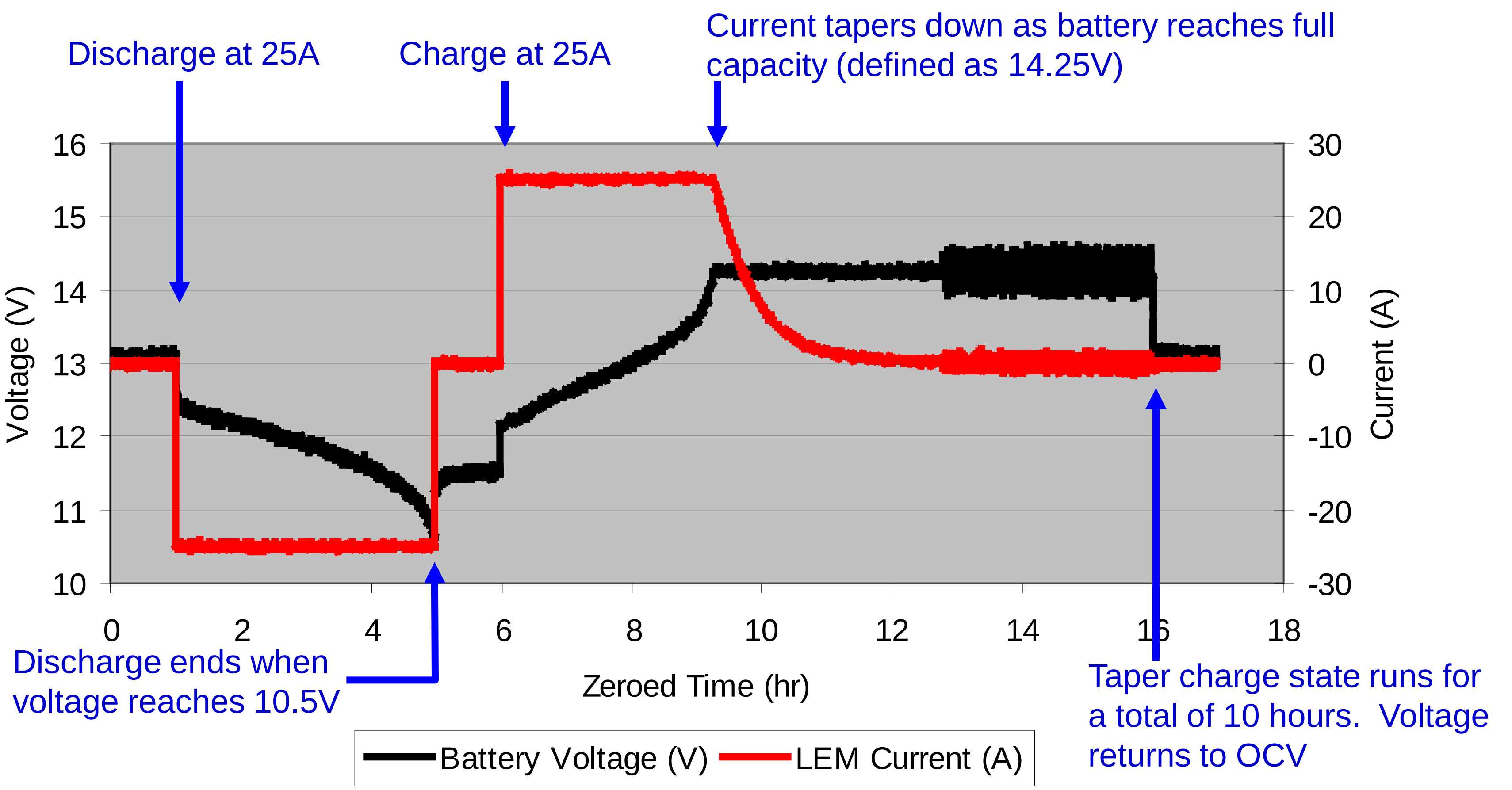


Environmental Test Chamber

Advanced Battery Tester Unit

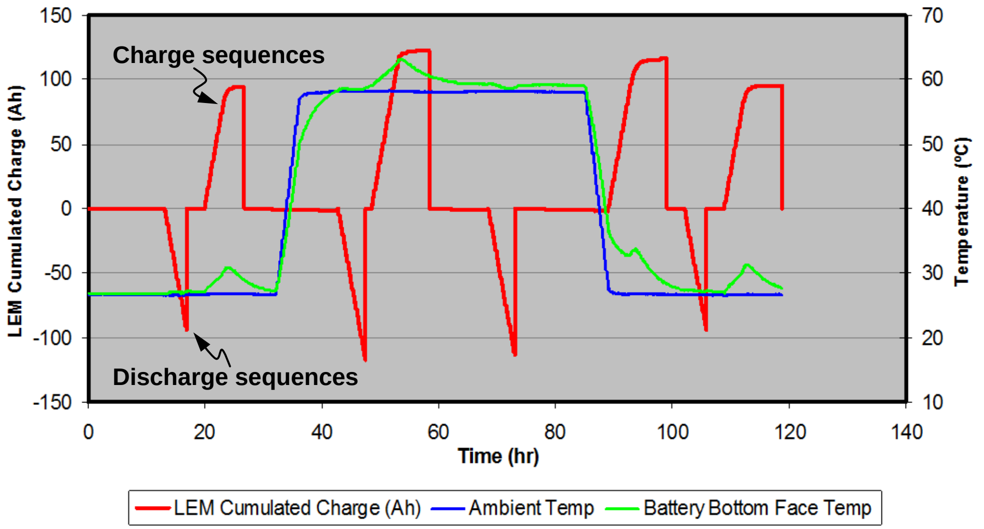
Environmental Testing
(Reserve Capacity Test)

- Environmental testing has used the standard reserve capacity test (MIL-PRF-32143A)



Environmental Testing *(General Procedure)*

- Batteries are initially tempered to median ambient temperature (27°)
  - Reserve capacity and recharge according to MIL-PRF-32143A
- Battery test article is tempered to target temperature
  - Reserve capacity test at temperature
  - Recharge at temperature
  - 2nd reserve capacity test at temperature
- Return to median temperature (27°C)
  - Recharge at median temperature
  - Post-temperature reserve capacity test
  - Recharge



Environmental Test Data Exemplar (60°C Test Sequence)

Direct Current Resistance *(Charging)*

- Battery DCR can be calculated from knowledge of the instantaneous OCV through:

$$DCR = \left| \frac{Cell\ Voltage - OCV}{Cell\ Current} \right|$$

- OCV is determined through SOC knowledge
- A correlation mapping DCR as a function of SOC and temperature was sought of the form:

$$\boldsymbol{DCR} = Ae^{-\alpha \boldsymbol{SOC}} + Be^{-\beta(1-\boldsymbol{SOC})} + C\boldsymbol{SOC} + D$$

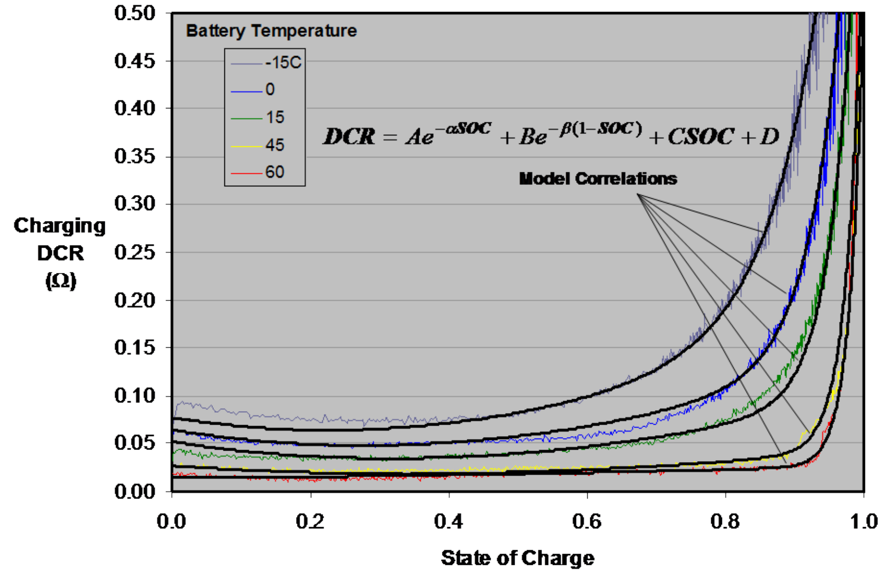
- Each of the coefficients are assumed linear functions of dimensionless temperature

$$Coefficients: (A, B, \alpha, \beta, C, D) = m\theta + b$$

where

$$\theta = \frac{T - T_f}{T_0 - T_f} \qquad T_f = -40°C \qquad T_0 = 25°C$$

- Good correlation to data implies linear temperature variation may be adequate assumption



Charging DCR as a function of SOC and Temperature

Coefficient	m	B
A	-1.113	1.753
B	-0.308	0.980
α	0.129	0.602
β	33.369	0.797
C	-0.616	0.982
D	1.059	-1.655

Correlation Coefficients

Direct Current Resistance *(Discharging)*

- Battery DCR can be calculated from knowledge of the instantaneous OCV through:

$$DCR = \left| \frac{Cell\ Voltage - OCV}{Cell\ Current} \right|$$

- OCV is determined through SOC knowledge
- A correlation mapping DCR as a function of SOC and temperature was sought of the form:

$$\boldsymbol{DCR} = Ae^{-\alpha \boldsymbol{SOC}} + Be^{-\beta(1-\boldsymbol{SOC})} + C\boldsymbol{SOC} + D$$

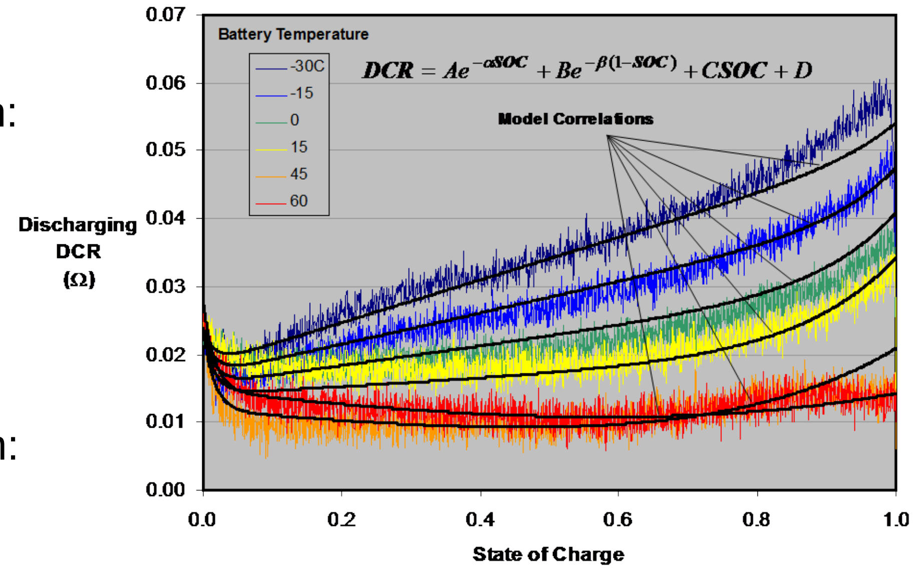
- Each of the coefficients are assumed linear functions of dimensionless temperature

$$Coefficients : (A, B, \alpha, \beta, C, D) = m\theta + b$$

where

$$\theta = \frac{T - T_f}{T_0 - T_f} \qquad T_f = -40°C \qquad T_0 = 25°C$$

- Poorer correlation to data than charging illustrates non-linear temperature behavior



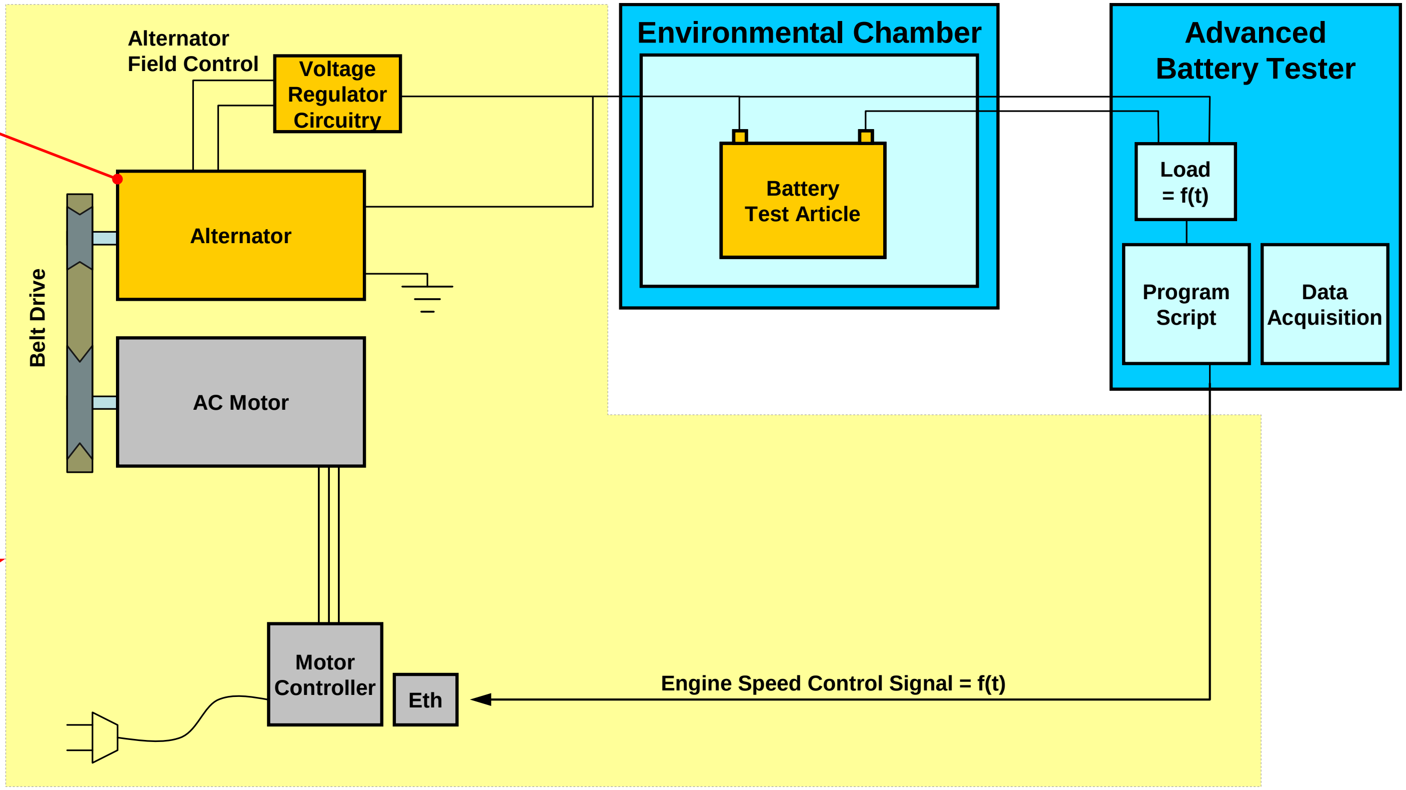
Discharging DCR as a function of SOC and Temperature

Coefficient	m	b
A	5.698E-03	4.647E-03
B	1.455E-02	2.159E-03
α	3.133E-01	6.282E+01
β	-7.978E+00	1.385E+01
C	-3.714E-02	3.712E-02
D	-6.255E-03	1.935E-02

Correlation Coefficients

Evolution of the Test Apparatus

- Addition of alternator to test apparatus permits "vehicle simulation"
- AC motor, with speed control, simulates engine crank shaft
- Battery tester acts as programmable load to simulate vehicle power draw
- C.E. Niehoff & Co. alternator model N1609-1

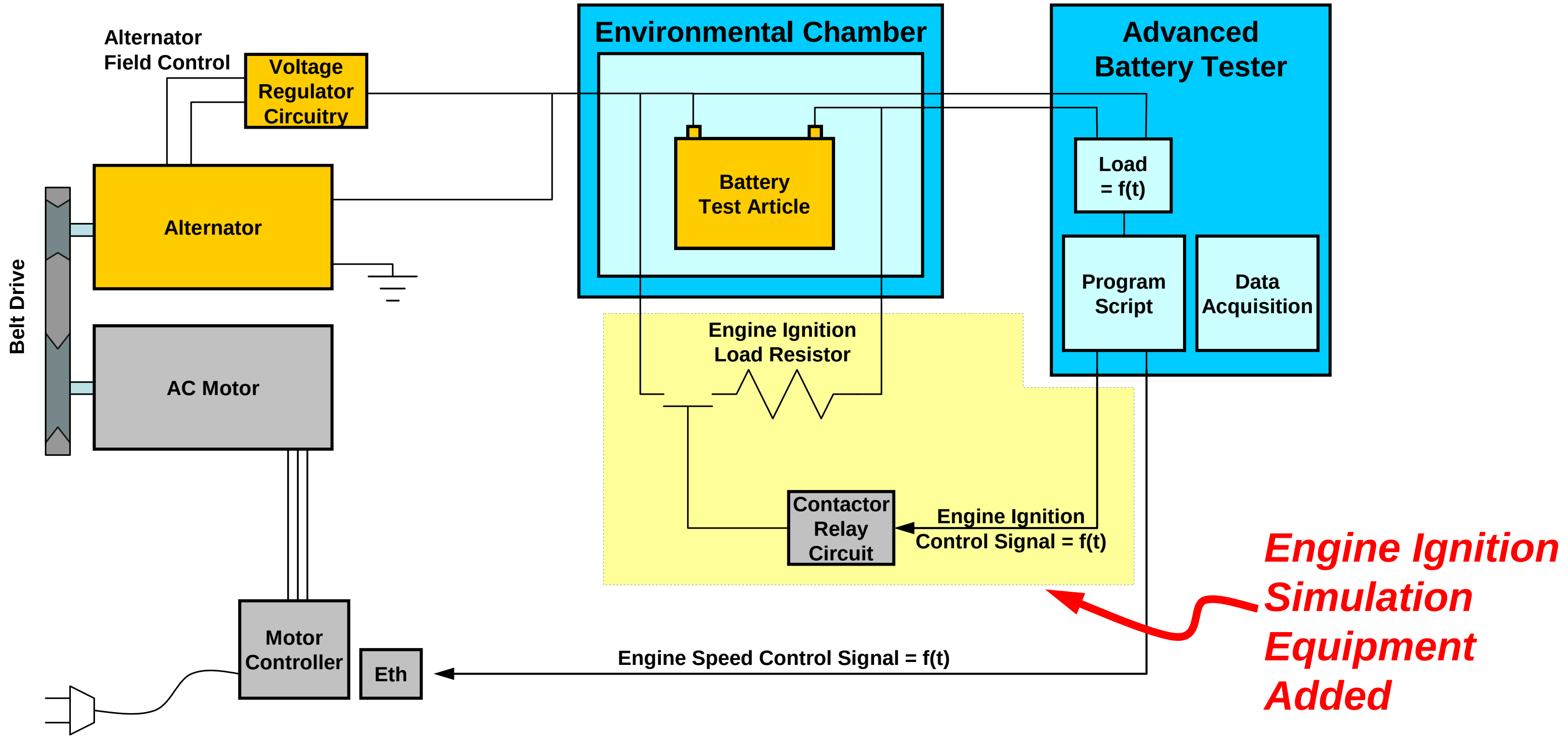


Alternator Equipment Added

Evolution of the Test Apparatus

POWER AND MOBILITY

- Addition of engine ignition resistor permits simulation of engine cranking
- Programmable relay control to ignition load resistor
- Battery tester acts as programmable load to "tune" ignition power draw



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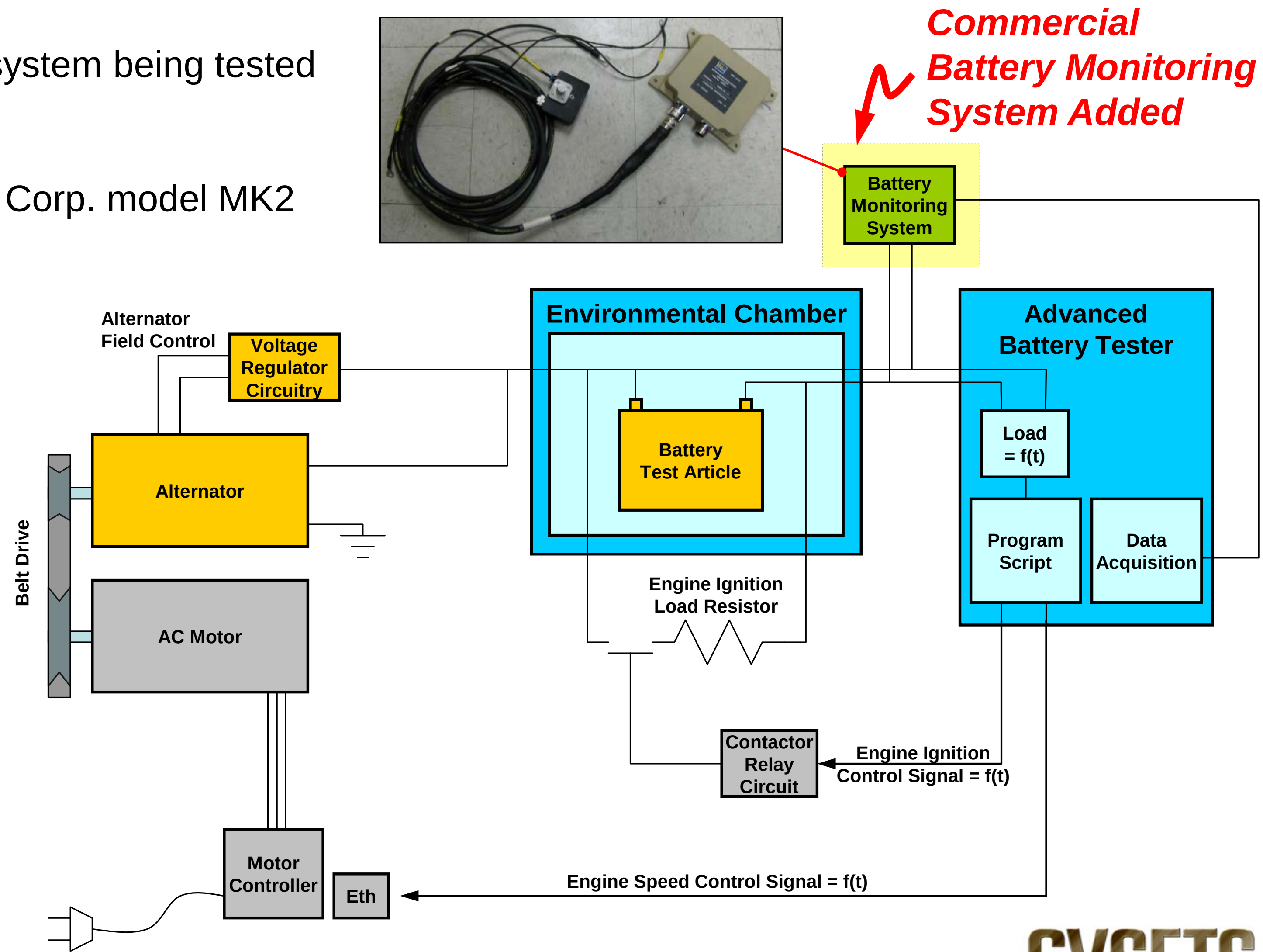
Evolution of the Test Apparatus
(Battery Monitoring System)

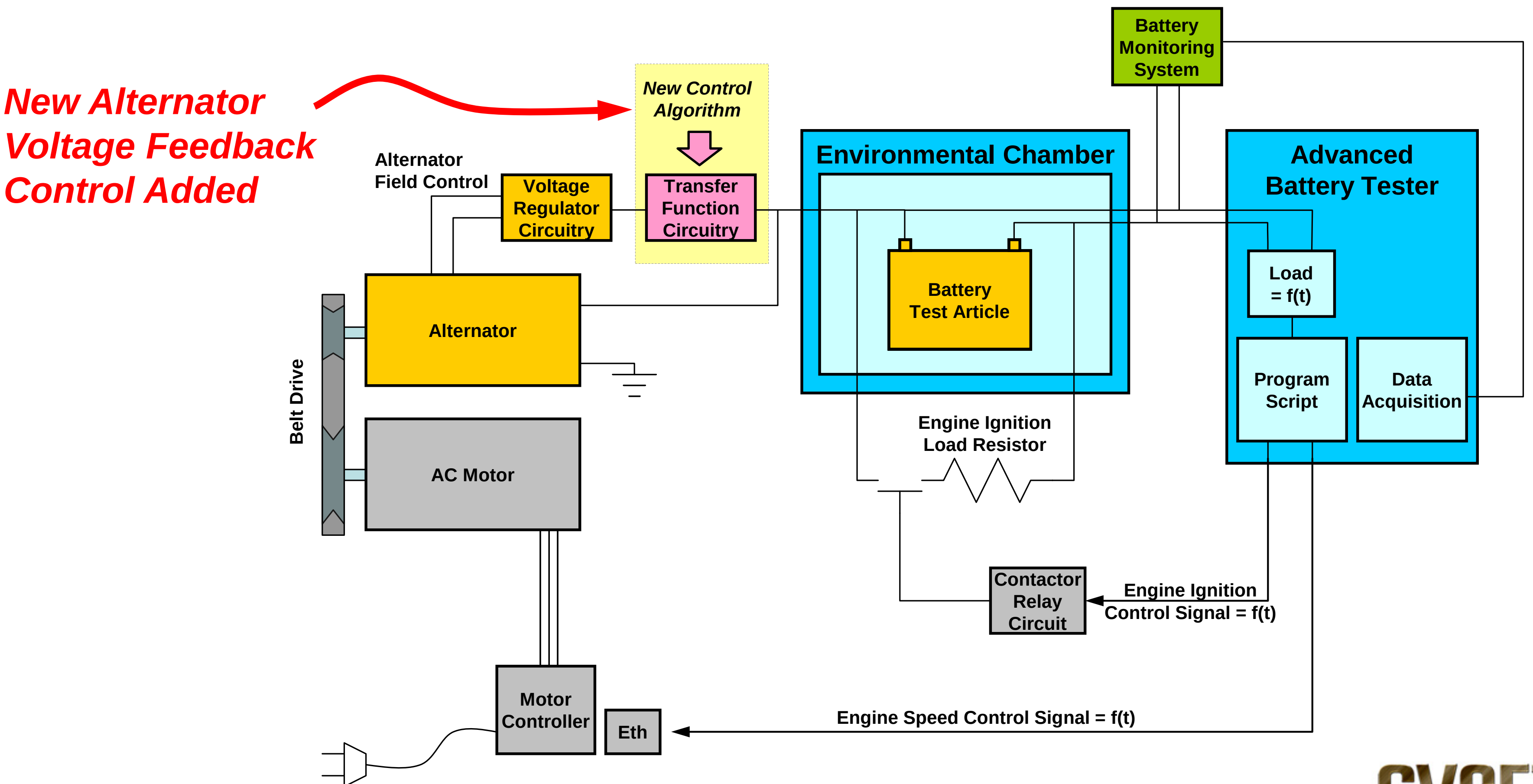
- Commercial BMS system being tested for data fidelity
- EMS Development Corp. model MK2 BMS
- Provide feedback for SOC, V, et al
- Compare accuracy to Advanced Battery Tester data



Evolution of the Test Apparatus *(Alternator Feedback Control)*

POWER AND MOBILITY

- Initially provide voltage feedback from Advanced Battery Tester controlled signal to provide programmable alternator voltage as a function of battery voltage, temperature and SOC
- Once optimized, look to develop electronics card for alternator feedback



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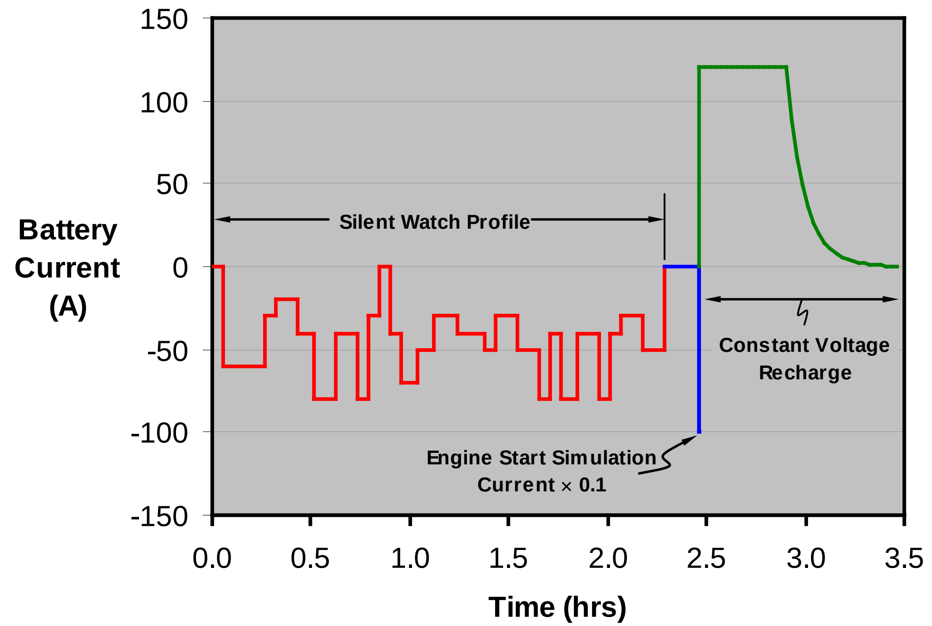
Scheduled Testing

- Test articles are currently being capacity tested to ensure "matching pairs" are used for 2-series connection
- Phase 2 testing will compare alternator fixed voltage algorithm to TARDEC-developed algorithm
  - Fixed charge-discharge profiles
  - Range of temperatures
- Phase 3 testing will simulate silent watch mode profile comparing algorithms
  - Simulated silent watch load profile
  - 10-minute rest
  - 1000 A engine simulation
  - Recharging algorithms
  - Range of temperatures



Silent Watch Mode Test Profile

- Currently completing integration of the test apparatus
- System will be able test a number of test profiles to include vehicle driving simulation (engine rpm response) and dynamic vehicle electrical loading